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EXPERIMENTAL STUDY OF BRIDGE PIER SHAPE TO MINIMIZE LOCAL SCOUR

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ABSTRACT

The study of local scour around bridge piers is very important for safe design of piers and other hydraulic structures. In this study, shape of pier is the main concern with three different velocities (0.18, 0.25, and 0.3) m/sec and other parameters like flow depth, bed material and etc. are remain same for all experiments. The experiments were conducted using laboratory flume, operated under the clear water condition using sand as a bed material. The test program was done on ten different shapes, Circular, Rectangular, Octagonal, Chamfered, Hexagonal, Elliptical, Sharp, Joukowsky, Oblong, streamline. were used to investigate the effect of the bridge pier's shape on local scour to conclude the optimal shape that gives minimum depth of scour. Comparison of results show that scour at upstream is directly proportional to exposed area of upstream nose of pier. The results showed that the rectangular pier gives the largest scour depth (7.6) cm, while the streamline shape gives the lowest scour depth (3) cm. The equilibrium scour depth of pier models compared with theoretical equations has been developed by some researchers and the results were very close.

Key words: Local Scour, Shape of Bridge Pier, Sand Bed

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1. INTRODUCTION

Scour is the lowering of the riverbed level by water erosion such that there is a tendency to expose the foundations of a bridge. The foundation of any hydraulic structure should be given the greatest importance in design and analysis as compared with other parts of the structure, because the foundation failure would destroy the whole structure. Local scour around bridge piers can cause a serious structural damage to a bridge by eroding the soil bed and destroys the foundation. The collapse of bridges can lead to significant damages can result in dangerous injuries or death.

Scour problem in New Zealand causes on average every year one bridge failure **(Melville and Coleman, 2000)**. **Arneson et al., 2012** quoted a study Conducted in 1973 for Federal Highway Administration (FHWA) of 383 bridge collapse because of flooding, 25% of pier damage and 75% of abutment damage. Also in 1987, floods have been occurred in New York and New England were destroyed and damaged about 17 bridges **(Hamil, 2000)**.

Different factors affect the process of scour around bridge piers and the flow pattern. This study focused on the influence of the bridge piers shapes on minimizing the local scour. The shape of pier is one of the important factors that play an important role in the creation and the strength of the vortex system. The system of vortex consists of horseshoe vortex, wake vortex system, trailing vortex system, and bow wave vortex **(Chiew, 1984)**. There are two types of piers, uniform (simple) piers and non-uniform piers (complex). Uniform piers are piers having a constant section throughout their depth and non-uniform piers include piers of piled foundations, slab footings, and tapered piers **(Melville and Coleman, 2000)**. This study is limited to only uniform piers and their effects on the depth of local scour.

Tison, 1940 and 1961 (quoted from **Breusers et al., 1977**) tested the influence of alignment and shape of pier on local scour in sand (d_{50} = 0.48) mm. He observed that the rectangular shape, the maximum scour depth. When the pier aligned with the flow, he observed that there is no influence of rectangular pier length on scour depth.

Jueyi et al., 2010 identified clear-water scour around semi-elliptical abutments with armored beds. Experimental study has been carried out under a clear-water scour condition to explore the local scour around semi-elliptical model bridge abutments with armor-layer bed, compared with the local scour process around semi-circular abutment. The researcher concluded that for both semi-elliptical and semi-circular abutments, with increase in flow velocity in all of the runs the equilibrium scour depth of the scour hole will be increased.

2. EXPRIMENTAL SETUP

2.1. Laboratory Flume

In order to achieve the mentioned purpose in this study, ten different pier shapes, rectangular, circular, oblong, hexagonal, octagonal and streamline were operated under clear water conditions in sand bed material. These models, located in the hydraulic laboratory of Kut Technical Institute, Iraq. The experiments are conducted in a flume with a closed-loop flow system. The flume is 12 m in length and 0.5 m in width. It has toughened transparent glass side walls with height of 45 cm. The general view of experimental flume shown in Photo 3.1. The working section 4.8 m was divided into two parts of 2.4 m, the second part filled with erodible uniform sand with depth 0.1 m. The inlet and outlet of working section contain raised gravels sloping ends of 1: 17 and 1: 20 respectively to provide uniform flow in test .The discharge

was measured by a V- notch fitted at the flume inlet. A moveable vertical gate is installed at the downstream to regulate tail-water depth. All depth measurements are carried out using two movable carriages with point gauges were mounted on brass rail at the top of flume sides, which have an accuracy of ± 0.1 mm. The velocity of flow was checked and measured by mini-water velocity meter of accuracy ±2% the velocity meter measures with a range (0 to 5) m/sec.

Figure 1 The used flume.

2.2. Pier Models

In this study, ten pier shapes was compared with each other, and no any attempt is made to simulate a real prototype. Piers were manufactured from 18 mm Medium Density Fiberboard (MDF) sheets. For high accuracy in models dimensions, the (MDF) sheets have been cutting by using a CNC routing machine. The MDF wood sheets were then glued and laminated together, painted with pigments and coated with varnish to increase its smoothness and to avoid MDF swelling of water.

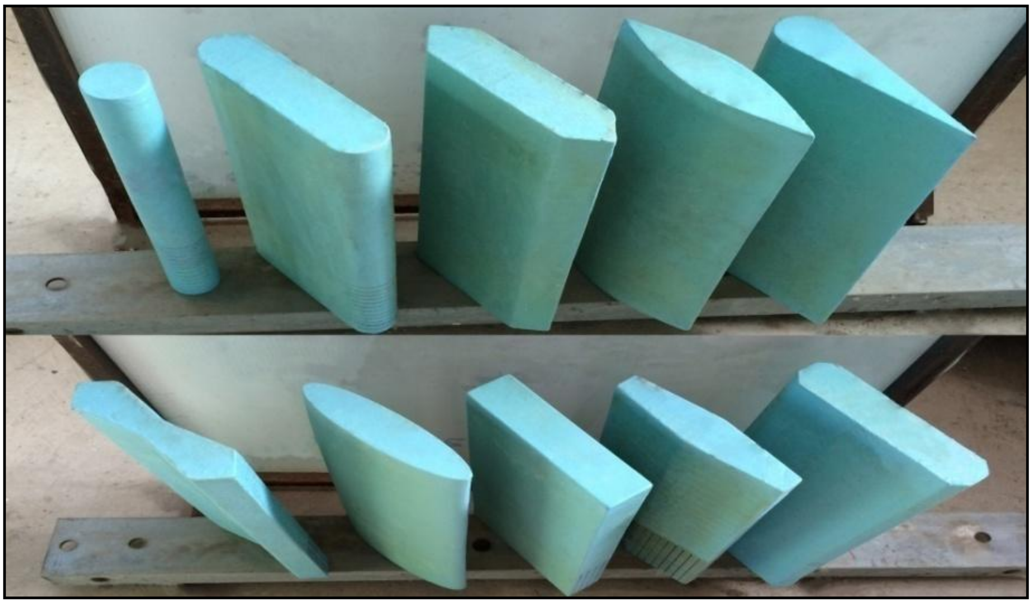


Figure 2 Piers models used in the experiments.

The pier models have a constant length to width ratio with (length/width=4). The experiments are conducted with a pier width of (4.5cm) at constant flow depth of 0.12 m by changing the shape of pier. According to **Chiew and Melville, 1987** recommendations, pier diameter should not be more than 10% of flume width to avoid wall effect on scouring. In this study, it is kept in mind that the width of the experimental flume is more than 10 times of the pier width, which satisfies the all criterion given by above researchers.

2.3. Bed Material

Mechanical sieve analysis test was carried out to characterize the sand bed material used for study. The results of the test showed that the material of bed with a median particle size (d_{50}) of 0.71 mm. The geometric standard deviation of the sand size, σg, is 1.14, which implies that the sand is of uniform size distribution. The σg is defined as, $\sigma g = (d_{84}/d_{16})^{0.5}$. The plot of the grain size distribution test is depicted in Figure 3.5. The pier diameter was also carefully chosen so that there was negligible effect of sediment size on the depth of scour. It is known that the bed material grain size does not affect the depth of scour if the pier width to grain size ratio exceeds a value of about 25 (**Melville, 1997**). For this study, the ratios are about 63.4 for the pier of 45 mm, which satisfies the criterion of **Melville, 1997**.

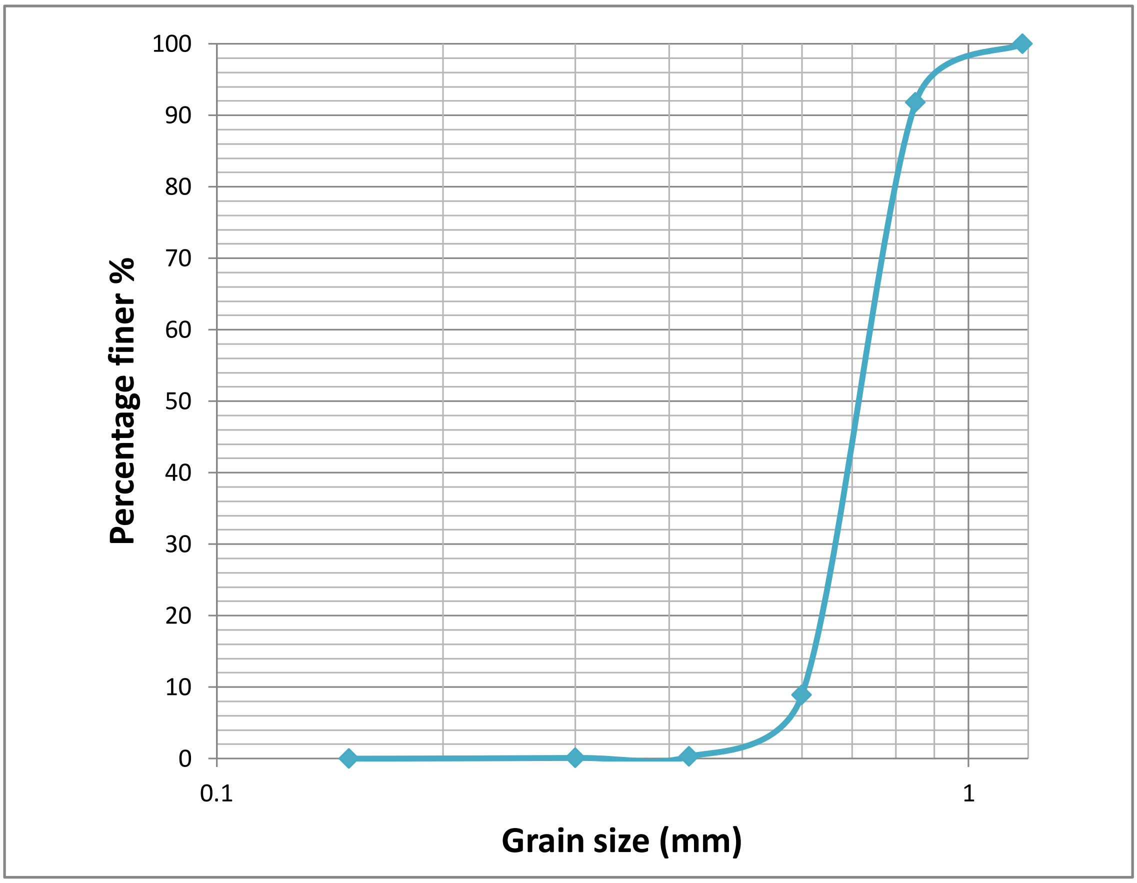


Figure 3 Grain size distribution curve.

2.4. Experimental Procedure

The following procedure was adopted for all experiments, which performed on steady subcritical flow at clear water condition with plain bed, i.e., no formation of ripple or dune through upstream portion at the working section:

- Pier models was fixed vertically to its place (within the middle of the working section).
- Bed of working section filled with a layer of sand with thickness of 10 cm.
- Bed surface was leveled using a scraper. Levels are also checked by using the point gauge.
- Tail gate is raised and the working area is filled with water by hose from the downstream portion of the flume in order to allow any air bubble to percolate out of the bed to avoid any settlement around the piers and to prevent any abrupt high velocity which causes the disturbance in sand bed after starting pumping.
- After starting pumping the tail gate is gradually lowered until the required water depth established in the flume. This depth is checked by a point gauge and the velocity also, checked by the velocity meter. The test is conducted over six hours.
- Time was recorded using a stopwatch during each test and at the end of time the flow is stopped then the scour depth is recorded using a point gauge.
- The flume drained slowly to avoid any change of the scour hole, the sand is allowed to dry and then the required measurements of sand bed upstream, downstream, longitudinally, and transversely are recorded.
- The sand was then re-leveled and the steps from (1) through (7) were repeated by changing the pier shape.

3. TEST PROGRAM

The test program was developed to deal with the pier shape as a mitigation technique against local scour, with a major focus on the time required to achieve an equilibrium scour condition. The test program was done on ten different shapes, Circular, Rectangular, Octagonal, Chamfered, Hexagonal, Elliptical, Sharp, Joukowsky, Oblong, streamline. Experiments were conducted under clear-water conditions at different water discharges 10.9 lit/sec, 15.42 lit/sec and 18 lit/sec and maximum depth of scour was measured. The test conditions for each shape of bridge piers are summarized in Table 1.

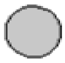
Table 1 Test condition for test series.

NO.	FLOW INTENSITY	Y (CM)	VELOCITY IN FLUME	Q (LIT/SEC)	FR	RE
1	0.56	12	0.18	10.9	0.166	14742
2	0.79	12	0.25	15.42	0.230	20817
3	0.92	12	0.30	18	0.276	24300

4. RESULTS

The summary of laboratory results that have been obtained from series tests conducted on the ten pier shapes are shown in Table 2. The figures 4,5,6,7 are the best shapes that gave the minimum scour depth while the figure 8 shows the contours line of scour hole around the best shapes in this study for maximum velocity (0.3) m/sec. The experiment study showed that scour drastically reduced with changing the pier shape and increasing with increases flow velocity. The results showed that the rectangular pier gives the largest scour depth (7.6) cm, while the streamline shape gives the lowest scour depth (3) cm.

Table 2 Measured scour depths of piers for tests series.

Pier Shape		V=0.18	V=0.25	V=0.3
		Measured scour depth (cm)	**Measured scour depth (cm)**	**Measured scour depth (cm)**
Circular		3.9	6.1	6.9
Rectangular		4.3	6.8	7.6
Octagonal		4.2	5.2	5.9
Joukowsky		4.7	5.5	6.1
Chamfered		4.1	5.9	6.7
Oblong		4.1	4.6	5.8
Elliptical		3.6	4.9	5.6
Sharp nose		3	4.5	4.9
Hexagonal		2.8	3.6	4.1
Streamline		1.9	2.6	3

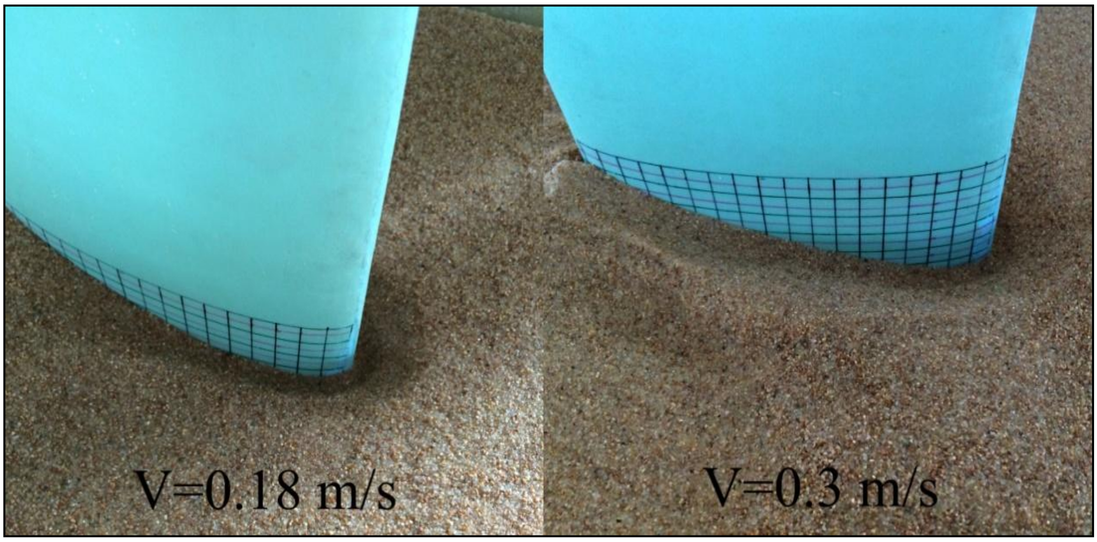


Figure 4 Scour pattern developed by minimum and maximum flow intensity (elliptical pier).

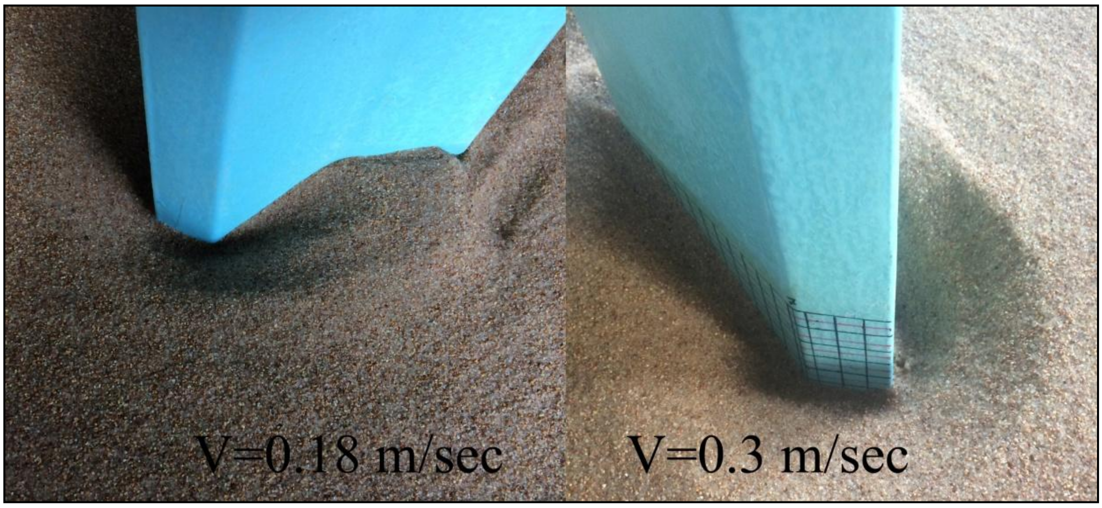


Figure 5 Scour pattern developed by minimum and maximum flow intensity (sharp nose pier).

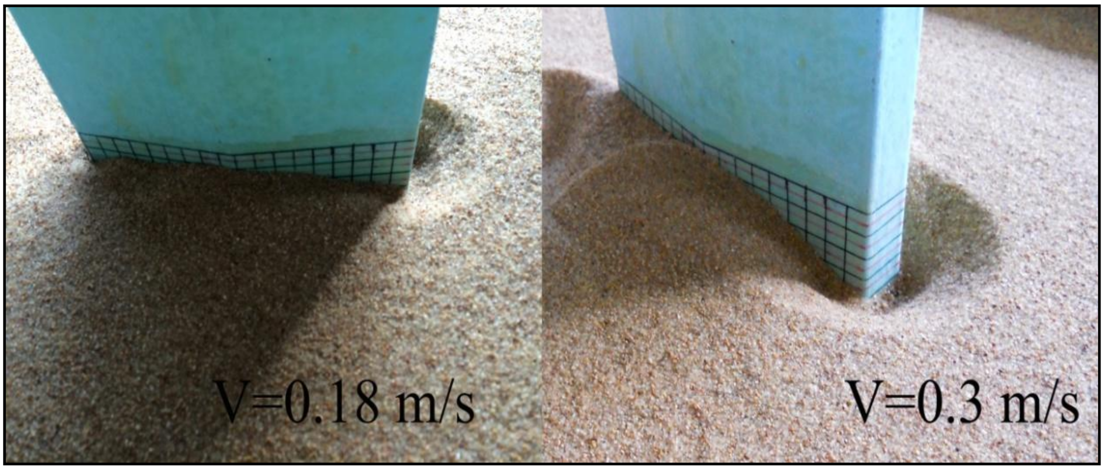


Figure 6 Scour pattern developed by minimum and maximum flow intensity (hexagonal pier).

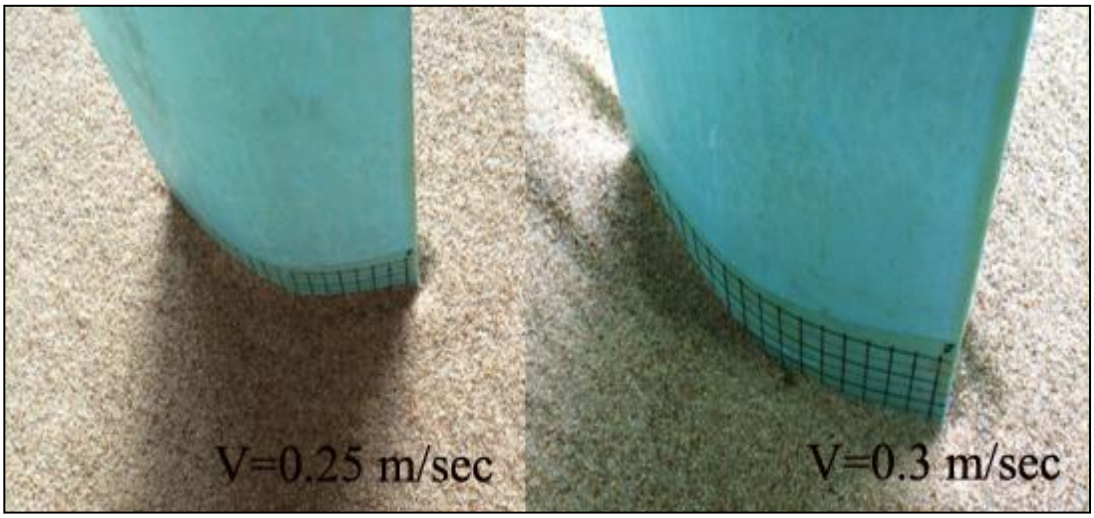


Figure 7 Scour pattern developed by average and maximum flow intensity (streamline pier).

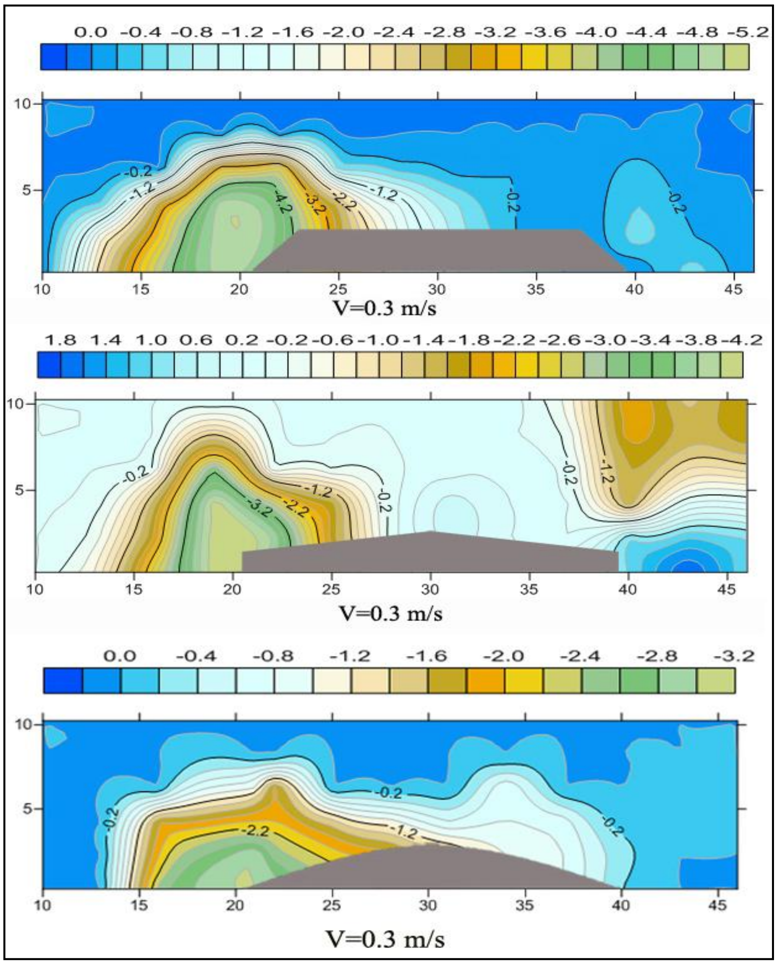


Figure 8 Scour contours for maximum flow intensities

5. DISCUSSION

The formation of horseshoe and wake vortices depends on shape of pier. Therefore, main intention of study was to investigate effect of pier's shape as protecting measure against local scour. Through a series of experiment on different shapes like rectangular, Oblong, Hexagonal, Elliptical, sharp and Streamline etc, it was observed that streamline pier is best protecting measure against local scour instead of other conventional shapes like rectangular, oblong etc. Theoretical explanation for it, the piers being an obstruction creates stagnation zone therefore when high velocity flow impact upstream side of pier it creates velocity jet that moves downward direction and creates scour hole. Although hexagonal and sharp pier also looks a like streamline with minimum upstream nose area, presence of corner causes higher scour at corner itself. It was observed that sharp pier and hexagonal pier's corner are starting point of local scour which propagates around the pier. For streamline pier, it was observed that scour started merely from upstream face and ends at mid section. Through this experimental observations it was concluded that rectangular pier have higher scour depth as compare to other shapes because of the maximum exposed area and streamline pier have lower scour depth because of the minimum exposed area. In an effort to analyze the data from this study further, Colorado state university (CSU) and Breusers et al., 1977, common equilibrium scour depth prediction equations as published in the literature were used to compare and compute the equilibrium scour depth to be expected for the test conditions applicable to each pier geometry. The reason for the analysis is to evaluate the usefulness of some of the famous equations

in the literature with a view of testing how reasonably they can predict the equilibrium scour depth based on the flow and sediment conditions used in this study. CSU and Breusers et al., 1977 formulas can be written as shown in equations 1 and 2, respectively.

$$y_{se} = 2k_{sh}\, y_0 Fr^{0.43} \left(\frac{b}{y}\right)^{0.65} \qquad 1$$

$$y_{se} = 1.35\, k_{sh}\; b^{0.7} y^{0.3} \qquad 2$$

Where: K_{sh} is the shape factor, it is a function of pier (length/width) in Breusers et al., 1977 equation, Fr is Froude number, b is the pier width and y is the flow depth.

Comparative results are shown in table 3. The parameters (flow depth, Froude number, pier width) were constant for all geometries except shape factor was variable. The shape factors were taken from different researchers including Tison, 1940, Laursen and Toch, 1956, Chabert and Engeldinger, 1956, Garde, 1961, Larras, 1963, Venkatadri et al., 1965, Dietz , 1972, Neill, 1973, Ettema,1980 and Richardson and Davis, 1995, except the shape factors of hexagonal and octagonal shapes, there are no values available in the literature. The values of measured scour depth agreed well with the values of theoretical equations that used in this study.

Table 3 Comparison with Colorado state university (CSU) and Breusers et al. (1977) formulas (V=0.3 m/sec).

No.	Shape	Shape Factor	Measured scour depth (cm)	Theoretical value (cm)	
				(CSU)	Breusers et al.,1977
1	Circular	1	6.9	7.4	8.15
2	Rectangular	1.11	7.6	8.2	9.05
3	Octagonal	-	5.7	-	-
4	Oblong	0.85	5.8	6.28	6.93
5	Joukowsky	0.88	6.1	6.50	7.17
6	Streamlined	0.48	3	3.54	3.91
7	Chamfered	1.01	6.7	7.46	8.23
8	Hexagonal	-	4.1	-	-
9	Elliptical	0.8	5.6	5.91	6.52
10	Sharp nose	0.7	4.9	5.17	5.70

6. CONCLUSIONS

The conclusions of this study were:

- Equilibrium depth of scour and initial scour rate depends on pier shape. Rectangular pier has a maximum exposed area that's why scour depth is much higher (7.6) cm than others shapes, while the scour depth for streamline geometry was (3) cm because it has a minimum exposed area without side corners, so scour rate and scour depth is minimum as compared to others shapes.

- The measured scour depth of pier models in this study agreed well with the calculated scour depth from theoretical equations (Colorado state university and Breusers et al, 1977).
- The streamline shape is considered the best shape of piers that reduces the maximum scour depth by 60% as compared with rectangular shape.
- It seen that, the scour depth increases as the flow intensity increases and vice versa.

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